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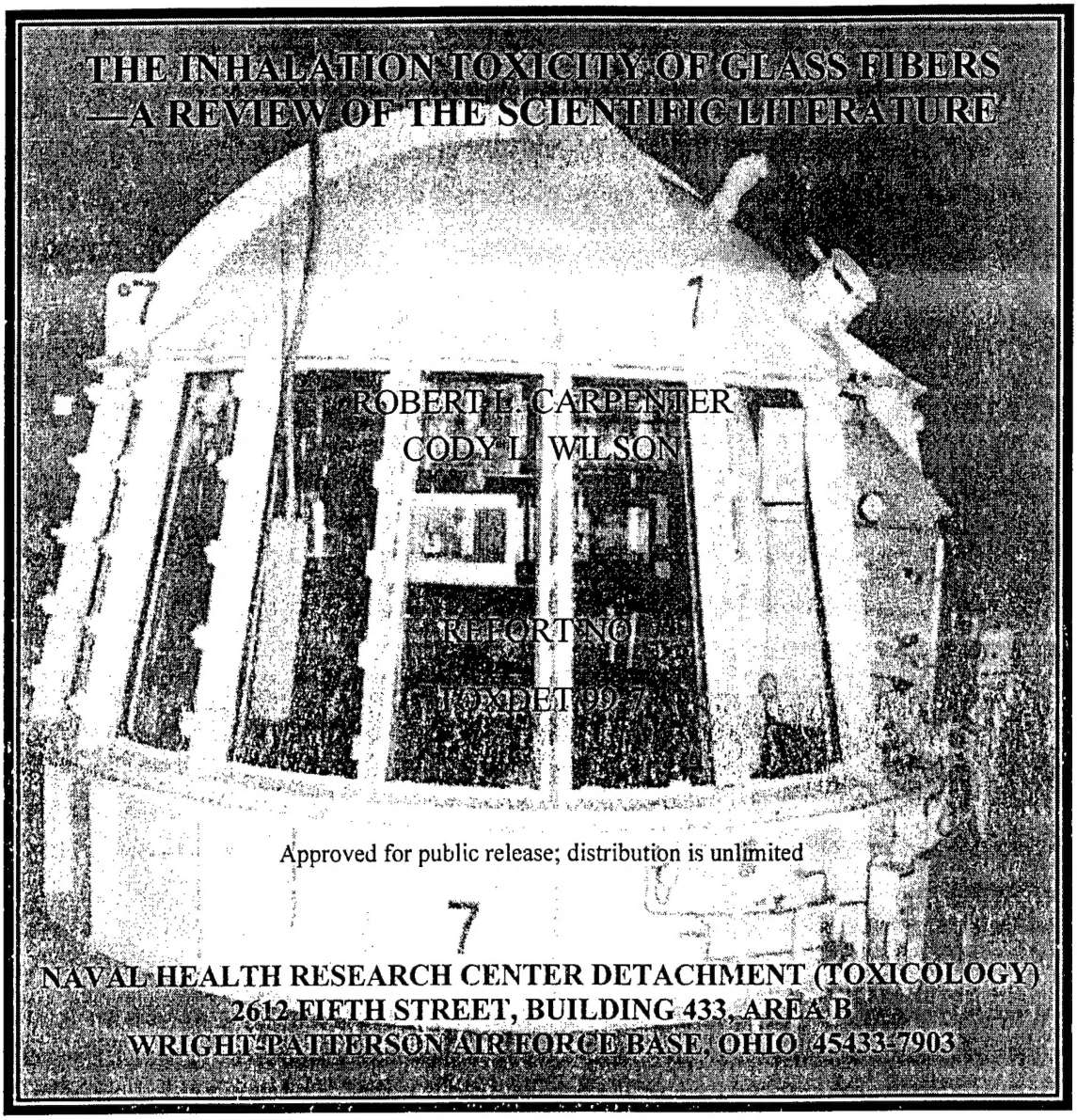
Naval Health Research Center Detachment (Toxicology)

THE INHALATION TOXICITY OF GLASS FIBERS —A REVIEW OF THE SCIENTIFIC LITERATURE



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The Inhalation Toxicity of Glass Fibers —A Review of the Scientific Literature

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PREFACE

This document reviews the scientific literature to define what information is available concerning fiber inhalation toxicology. This review has been prepared by the Naval Health Research Detachment (Toxicology) in response to concerns expressed over the potential hazards that might be associated with the release of chaff fibers during training exercises by Naval aviators. The fiber toxicity literature is voluminous because of the public health concerns arising from the asbestos-related lung cancers among asbestos workers. Since the decade of the 60's, it has become evident that some types of fibers produce serious lung disease. Recent European research has demonstrated that the potential for lung disease is related to the durability of long, thin fibers if they are small enough to be deposited in the deep lung. Chaff used as an electromagnetic countermeasure is made of non-durable glass and is manufactured to closely held dimensional tolerances. Physically chaff fibers are 10-100 times too large to be inhaled and reach the deep lung. As discussed in this report, these factors suggest that the inhalation toxicity of chaff fibers is extremely low. This work was sponsored by the Naval Air Warfare Center under Work Unit # 63706N-M00095.004.1822 and was performed under the direction of CAPT Kenneth R. Still, MSC, USN, Officer-in-Charge NHRC/TD.

The opinions contained herein are those of the authors and are not to be construed as official or reflecting the view of the Department of the Navy or the Naval Services at large.

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EXECUTIVE SUMMARY

PROBLEM

Chaff used to provide protection against radar based attack on aircraft and other military vehicles is composed of aluminum coated glass fibers. Concern has been expressed as to the environmental hazard and potential for human health risk associated with routine release of this material during training exercises.

OBJECTIVE

Since the health effects of inhaled fibers have been extensively studied, the scientific literature concerning the toxicity and carcinogenicity of inhaled fibers has been reviewed to determine what past research suggests as the potential for chaff to be an inhalation hazard.

RESULTS

Extensive research has been conducted over the past 34 years on the subject of the toxicity of inhaled fibers. This research has considered numerous fiber types and has examined the relationship between fiber toxicity and fiber size, composition, and lung biopersistence. Due to the ubiquitous use of fiberglass insulation, glass fibers have been extensively studied. This data bears on the toxicity of glass chaff fibers. The key fiber properties related to toxicity found to date are fiber length and fiber biopersistence. This evidence is strong enough to prompt the European Union to issue regulations concerning classification of fibers as hazardous substances based on measures of these properties.

CONCLUSION

The scientific literature supports the conclusion that chaff does not constitute an inhalation hazard. Chaff fibers are too large to reach the deep lung. They are made of glass and they should have low biopersistence. Efforts to develop a degradable chaff will further decrease chaff biopersistence.

ABSTRACT

Studies of workers occupationally exposed to asbestos revealed increasing incidence of mesothelioma, a rare form of lung cancer, whose underlying cause became clear in the 1965-1975 time frame (Selikoff *et al.*, 1972; Selikoff *et al.*, 1964; Selikoff *et al.*, 1979), creating concern as to the causes of this disease and as to the properties of asbestos leading to this disease. Asbestos exposure can cause other forms of lung disease such as fibrotic lung disease leading to severe, chronic respiratory distress. Since fibrous materials play such a key role in many facets of industrial and private life, numerous research studies of many fibers have taken place in the intervening 30 years. The purpose of this document is to provide the reader with needed background, summarize those investigations relevant to chaff health effect concerns and provide some insight as to the relevance of those concerns. Fibers differ from more spherical dust particles in their aerodynamic properties. For most dust particles, the particle's diameter and mass govern their persistence in the atmosphere. These properties also govern the particle's transport properties and their ability to penetrate the respiratory system. For fibers, the fiber diameter predominately controls its aerodynamic behavior with a weak effect from fiber length. However, since the air flow through the pulmonary conducting airways is turbulent in the regions where these airways branch, fiber length plays a large role in deposition at these branch points (bifurcations). This behavior makes fiber dose to airways bifurcations particularly high. In contrast, lung deposition of spherical particles is more uniform. The research on non-asbestos insulation fibers has demonstrated that, with few exceptions, asbestos is uniquely carcinogenic. Asbestos carcinogenicity is related to the type of asbestos, with blue chrysodilite asbestos being the most carcinogenic (toxic). Delineation of the asbestos properties leading to its unique toxicity has been the focus of much effort. Research over the past thirty years has revealed that fiber size plays a key role in fiber toxicity; fibers must be less than 0.2 micrometers in diameter and longer than 10 micrometers in length to be toxic. In part, this observation is explainable by fiber aerodynamics; fibers larger in diameter are too large to penetrate the upper respiratory tract and fibers must be long both for enhanced deposition and to foil the lung's natural defenses. The crystalline structure of fibers such as chrysodilite asbestos appears to be significant in triggering a biochemical response that leads to mesothelioma. Recent studies have provided substantial proof that fiber durability in the body is a key determinant of carcinogenicity. Fibers must persist as long particles for long times in order to reach sensitive tissues and evoke a carcinogenic response. Thus, biopersistence is key to fiber carcinogenicity. These research data allow prediction of chaff toxicity. First, chaff dimensions are carefully controlled as part of the requirement for effectiveness. The dimensions of currently deployed chaff are extremely large compared to the respirable cut-off of 0.2 micrometers, ensuring that few chaff fibers will enter the lower respiratory tract. Furthermore, the glass structure of the chaff fiber matrix is non-crystalline and should not be biopersistent. Current activities to design rapid dissolution into deployed chaff decrease the possibility that chaff fibers will be biopersistent. From these observations, it can be deduced that the fibrous nature of chaff should not pose a respirable hazard.

KEY WORDS

Chaff, inhalation toxicity, carcinogenicity, biopersistence, solubility, fiber length, fiber composition.

LIST OF ABBREVIATIONS

Note common chemical and measurement abbreviations are not included.

D_{ae}	aerodynamic diameter
d_{real}	measured particle diameter
β	ratio of fiber length to diameter

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INTRODUCTION

Naval Air Warfare Center (NAW/NAVAIR) requested the assistance of Naval Health Research Center Detachment, Toxicology (NHRC/TD) to resolve issues surrounding the perceived hazards of chaff dispersal over Navy test ranges involving both marine and terrestrial environments (General Accounting Office, 1998). In addition to environmental concerns, questions had been raised concerning human health effects. This report is in response to concerns regarding the potential inhalation hazard of chaff fibers.

The chaff materials used by the Navy and Marines consist of aluminum coated glass having specific lengths and diameters (approximately 0.001 inch in diameter and 0.37-2 inch in length). Developmental EcoChaff™ fibers have a diameter of approximately 1 mil [0.9 mil degradable vitreous oxide (DVO™); 0.1 mil aluminum]. In response to concerns over environmental persistence of chaff materials similar to soda-lime glass, NAWC began the development of EcoChaff with the intention of designing specific environmental degradation characteristics into the material. EcoChaff™ is an aluminum-coated DVO™. DVO™, which is a mixture of sodium and silicon oxides that are processed to exist in a non-crystalline, vitreous state. Because the sodium oxides in the network are moisture sensitive, when DVO™ is exposed to moisture, the strength and structure of the substrate deteriorates until it degrades into fine particles. As the substrate breaks apart, it also breaks down the aluminum coating. Depending on the environment, the degradation process may take weeks or months. The final degradation products will include silicon dioxide, sodium aluminate, and aluminum trihydrate (aluminum hydroxide). These materials are all commonly found in U.S. households. Aluminum hydroxide is commonly used as an antacid and in antiperspirants. Sodium aluminate is used as a water softener and in the textile industry. Silicon dioxide is a primary component of many glasses and is commonly known as silica. Thus, DVO™ breaks down into non-toxic compounds encountered by humans and animals on a frequent basis.

THE RESPIRATORY TRACT

Figure 1 is a schematic illustration of the human respiratory system delineating its major features.

Fiber inhalation results in deposition of the fibers within the respiratory system. This process is governed by the aerodynamics of fiber movement in the respiratory air flow which depends on both the geometry of the respiratory system and the fibers. The following briefly describes the feature of the human respiratory system that govern deposition and subsequent toxicity of fibers.

The major function of the lung is gas exchange, removing CO_2 from the body and exchanging it for oxygen (Guyton, 1969). This process requires a large surface area that is supplied with a continuous flow of air. The respiratory system can be divided into two major regions, one concerned with the distribution of inspired air and one that is concerned with the exchange of oxygen and carbon dioxide. The conducting airways of the lung consist of a series of branching tubes, the bronchii, that serve to humidify inspired air and distribute it to the respiratory tissues in the lung, the alveolar region. The alveolar sacs are closely associated with blood capillaries. Gases pass through the alveolar wall and blood capillary walls by diffusion. This architecture is illustrated in Figure 2.

As a result of this geometry, the cross sectional area of the lung air space increases dramatically as one progresses down the conducting airway tree. Linear air velocity also decreases as one progresses down the conducting airway tree, strongly influencing the deposition of fibers and other particulate matter. Table 1 illustrates the extent of these changes. Note that from the entrance of the lower respiratory tract, the trachea, to the gas exchange regions of the lung, the airway cross sectional increases by a factor of 10,000 and the air velocity decreases correspondingly (Lippmann, 1977). The air residence time increases by more than tenfold.

Functionally, the respiratory system is a re-entrant air pump. This gives rise to an airflow pattern in which air is first inspired into the lungs; there is a brief pause; and air is then exhaled.

This reversing, pulsatile, air flow creates significant turbulence in the conducting airways. This turbulence combined with the airway branching patterns, gives rise to high fiber deposition at the airway junctions (Lippmann, 1990; Asgharian *et al.*, 1999; Balàshàzy *et al.*, 1999; Hashish *et al.*, 1998).

As illustrated in Figure 2, the air spaces of the lung occupy most of the available volume. The space between alveolar sacs, the interalveolar septum, contains blood capillaries and connective tissue, which forms a supporting web for the mechanically weak alveolar structures. This space is part of the lymphatic system of the body and is drained by a flow of lymphatic fluid through the lung-associated lymph nodes, which act as an exit filter for the lymphatic fluid. This space, the intersititium, can become contaminated with fibers.

AERODYNAMIC PROPERTIES OF AIRBORNE PARTICLES AND FIBERS

For particles to be inhaled, they must be caught in the air flowing into the respiratory system and be trapped therein. To reach the deep lung, individual particles must be small enough to travel through the nares in the upper respiratory tract. At any point in the respiratory tract, particle trapping requires that the particles move to the walls of the tubes bounding the flow, requiring the particles to move across the direction of flow. For both transport and deposition, particle aerodynamic properties are the dominant factor. This section will discuss those aerodynamic properties governing particle deposition in the respiratory system and introduce the needed nomenclature. For a general discussion, the reader is referred to Hinds (Hinds, 1982).

Two extreme cases exist for drag forces on particles traveling through air. If particle size and velocity are large, the inertia of the air being pushed out of the particle path gives rise to the dominant drag on the particle. This force depends on the square of the product of particle velocity and diameter. Motion under these conditions is termed inertial motion and the relationship is known as Newton's Law. If the particle velocity and size are small enough that the air flows around a moving particle with no turbulence, the dominant drag force arises from the viscous behavior of the air. In this case, the drag depends on the product of particle diameter and velocity. This motion is termed viscous and the relationship is known as Stokes' Law.

The case of a particle settling through air is significant for deposition in the respiratory tract. During settling, gravitational and drag forces on the particle are in equilibrium and the settling velocity depends on the square of particle diameter. These relationships hold rigorously for spherical particles but actual particles vary in shape and density. In order to facilitate discussion of such particles, several definitions are of use. For particles of density other than one, the *aerodynamic diameter* of the particle is defined as the diameter of a unit density spherical particle having the same settling velocity as the actual particle. For nonspherical particles, a *dynamic shape factor* can be applied to the drag force of Stokes' Law to define a correction to the particle aerodynamic diameter. This corrected aerodynamic diameter describes the nonspherical particle settling properties.

Fibers differ greatly from spherical particles in shape. Aerodynamic considerations suggest a division between compact particle behavior and fiber behavior when the length/diameter ration exceeds ten. Gross (Gross, 1981) has demonstrated that fiber aerodynamic diameter is given by:

$$D_{ae}=66d_{real}(\beta/(2+4\beta))^{2.2}.$$

For respirable, long fibers, this relationship is approximately three to four times the actual fiber diameter.

FACTORS GOVERNING DEPOSITION IN THE RESPIRATORY TRACT

There are four basic mechanisms by which particles deposit in the respiratory system if they carry little electric charge, inertial impaction, diffusion, gravitational settling, and interception. The interplay of these mechanisms at different locations in the respiratory tract governs the deposition of particulate matter. Deposition by inertial impaction occurs when a particle collides with the lung air space surface because its inertia prevents it from following the airflow around the surface. Conducting airway bends and airway branches are regions where impaction is an important deposition process. Diffusion arises from the Brownian motion of small particles caused by the uneven distribution of collisions with air molecules. If a particle is traveling close to an airway surface, diffusion can move it laterally and it can contact the wall. Deposition by

diffusion is most prominent where air velocities are low as in the terminal bronchioles and alveolar sacs. Gravitational settling has been covered in the discussion of particle aerodynamic behavior. The force of gravity acting on particles in the respiratory tract will move particles across the airflow until they contact an airway wall. As with diffusion, gravitational settling is most important in the terminal bronchioles and the alveolar spaces of the lung. Interception is the process by which a particle contacts an airway wall because the path of the air containing the particle collides with the wall. From geometric considerations, the probability of interception is greater for larger diameter particles and predominates at bends and airway branches. Interception is particularly important for long fibers, where one dimension is much larger than the other. In turbulent airflow, fiber tumbling increases the space swept by the fiber, greatly increasing the probability of deposition by interception.

It follows from this discussion that particle deposition in the respiratory tract is a complex function of breathing patterns and location within the respiratory system. Figure 3 illustrates an experimental set of total lung deposition data for nearly spherical particles. A number of investigators have demonstrated that fibers deposit according to their aerodynamic diameter but that the airway branching points (airway chorina) are hot spots for fiber deposition (Asgharian and Ahmadi, 1999; Dai *et al.*, 1999; Griffis *et al.*, 1983). Brody and co-workers have demonstrated that fiber deposition at the chorina is significantly enhanced for fibers (Brody *et al.*, 1981).

FIBER TYPES

There are a wide variety of man-made and naturally occurring fibers present in the environment. The utility of fibrous materials continues to spur development of new fibers. Since the recognition of asbestos as a carcinogen, there has been a worldwide concern over whether other fibers are carcinogenic. This has led to significant research into the toxicity and biological properties of fiber materials.

ASBESTOS

Asbestos seems to hold a unique position among fibers with regard to its biological properties. The term asbestos is not mineralogically unique, but is defined to mean a naturally occurring inorganic, hydrated silicate that exists in layered structures composed of chains of silicon/oxygen tetrahedra which can subdivide into flexible fibers. There are two mineralogical types of asbestos, serpentine and amphibole. The asbestos form of serpentine is chrysotile, while the most common types of amphibole asbestos are crocidolite (blue asbestos) and amosite. These account for most of the asbestos produced commercially. Amphibole asbestos has a unique mineralogical property of splitting lengthwise into increasingly smaller diameter fibers, while not decreasing appreciably in length, leading to the production of many, highly respirable fibers of greater that 100:1 aspect (length to diameter) ratio. These properties combined with the surface crystalline structure appear to be strongly related to its carcinogenic potential. Much has been written about asbestos as a uniquely hazardous material and as a prototype for other potentially hazardous fibers. The reader is referred to the Toxicological Profile for Asbestos (ATSDR, 1995) and to the ASTM publication (Grand, 1990) for further information concerning asbestos and the diseases caused by it. Brody has demonstrated the persistence of asbestos fibers in the lung (Roggli *et al.*, 1984), showing that long fibers can persist for prolonged times and migrate from airway deposition sites to the pulmonary intersitium in a remarkably short time (Brody *et al.*, 1984; Roggli *et al.*, 1986). Long fibers appear to activate lung defenses associated with macrophage cells (Brody, 1989; Warheit *et al.*, 1982; Warheit *et al.*, 1984a; Warheit *et al.*, 1984b; Warheit *et al.*, 1985).

MINERAL WOOL

Mineral wool or rock wool fibers are produced from molten slag materials and have commonly been used as insulation in building construction. They are amorphous, glass-like substances of relatively large aerodynamic diameter.

GLASS

Glass fibers are produced from molten glass in a variety of sizes and compositions for use as insulation materials either as batts bound together with epoxy resins or as loose fibers. With improvements in technology and the need for better insulation materials, fiberglass insulation materials containing respirable fibers have been produced commercially.

CERAMIC

Development of ceramic fibers is being actively pursued in effort to develop superior, high temperature insulation materials and replacement materials for asbestos. Ceramic fibers having properties similar to asbestos have been produced, but these materials also show some of the biological properties of asbestos.

ORGANIC

Organic fibers are produced from high-strength, plastic materials for use as fabrics and for reinforcement of engineered structures. Most of these fibers are sufficiently large in diameter that they do not constitute a respirable hazard, but mechanical abrasion and chemical decomposition of some materials may result in respirable fibers.

FATE OF INHALED FIBERS

After fiber inhalation, the respiratory system responds to the presence of these foreign bodies with the defense mechanisms that are employed to remove or degrade other particulate matter. Much of the conducting airway tree is lined with ciliated cells and coated with a mucous layer. Fibers deposited on these surfaces are removed by the flow of mucous out of the respiratory tract and into the esophagus. However, the lower regions of the airway tree and the respiratory tissue of the lung do not have a mucous lining and other means of defense are employed. The lung is particularly rich in macrophages, a free-roaming lymphatic cell capable of surrounding and internalizing foreign materials (phagocytosis). In the normally sterile

environment of the pulmonary alveolus, there exist only a few macrophages per alveolus. However, after deposition of fibers or other foreign materials, macrophages are rapidly recruited and the number of macrophages per alveolus increases dramatically. These cells are activated and quickly engulf foreign particles that are not larger than they are. Studies with rats indicate that fibers shorter than 20 micrometers can be phagocytized. Once engulfed, enzymes inside the macrophage cytoplasm are capable of destroying the engulfed particle. Macrophages are also capable of migrating through the pulmonary lymphatic system resulting in foreign material transport out of the lung.

TRANSLOCATION

Brody (Brody *et al.*, 1981) demonstrated that asbestos fibers move rapidly from their deposition site into the interstitium of the lung. This behavior seems to be key to a process which results in tumors on the outside surface of the lung arising from materials deposited throughout the volume of the lung. In addition to the role of macrophages, translocation seems also to be affected by the lung's mechanical motion during the act of breathing. The long-term effect of these processes is the accumulation of fibers in nodules throughout the lung and the movement of fibers from relatively even distribution throughout the lung to a layer just below the outer surface of the lung.

FIBER DESTRUCTION

Fibers that are soluble in the pulmonary environment will gradually dissolve even if too long to be phagocytized. Complete dissolution of these fibers leaves the alveolus in its original sterile state and lung response decreases to a normal quiescent state.

If materials fail to be removed from the lung, then they must be either isolated or destroyed. The lung has a great capacity to absorb foreign bodies with little impact, as evidenced by the sooty lungs of any city dweller. Isolation of particulate matter, following long term high level exposure, can be followed by measurable lung dysfunction in such diseases as emphysema and industrially related lung diseases such as coal workers pneumoniconosis. Microscopic evidence

indicates that lung macrophages respond strongly to inhaled asbestos fibers and to other fibers to a lesser extent. For long fibers, this response includes macrophages being pierced by fibers too long for them to engulf. One hypothesis of fiber toxicity asserts that the destructive enzymes released under these circumstances give rise to tissue damage that further excites lung responses. Evidence suggests that an important factor in asbestos toxicity is its ability to persist for a long time.

Glass, mineral wool, and some ceramic fibers do not remain as long fibers after lung deposition, in contrast to asbestos, Over time, these fibers break transversely to their long axis, shortening until they can be engulfed by macrophages. Phagocytosis and subsequent dissolution remove the shortened fibers. Some of these fibers are also seen to be bio-soluble, and removal be dissolution aids in removal.

BIOLOGICAL RESPONSE TO FIBERS

Epidemiological studies of workers in the different fiber industries exhibit increased incidences of respiratory cancers and all are fibrogenic to one degree or another. These studies support the relative safety of non-ceramic fibers, particularly in comparison with asbestos. However, IARC has taken the conservative approach of classifying fiberglass, rock wool, and refractory ceramic fibers as Class 2B, "possibly carcinogenic to man," and the U.S. lists fiberglass as a substance which may reasonably be anticipated to be a carcinogen.

Animal studies vary in their findings, which range from no remarkable observations in some glass fiber studies using rats and hamsters to fibrotic lung damage in other studies. Carcinomas have resulted from inhalation exposure of rats to glass fibers. Adenomas have resulted from inhalation exposure of rats to glass fibers and rock or glass wool and of guinea pigs to glass fibers. Staunton (Stanton *et al.*, 1981) demonstrated that fiber length and diameter are critical to the carcinogenic potential. He found that fibers longer than 8 microns and less than 0.25 microns in diameter had the highest carcinogenic potential when implanted in the chest.

BIOPERSISTENCE

The concept of biopersistence as an important factor in fiber toxicity arises from studies of both natural and man-made fibers. A number of studies have indicated that fibers have very different lung retention characteristics. Some fibers (asbestos) persist for longer periods of time while others, such as some of the glass fibers, persist for a much shorter time. Investigations of lung tissue, upon autopsy of individuals who died with mesotheliomas and were exposed to a mixture of amphibole and chrysotile asbestos, demonstrated that even when chrysotile had been the dominant fiber in the inhaled mixture, amphibole fibers were the dominant remaining fiber in the lung. Animal studies of response to inhaled fibers indicate that those with the highest fibrogenic or carcinogenic potential were also the most persistent fibers in whole animal or laboratory dissolution experiments.

Biopersistence is defined to reflect the processes that remove inhaled material from the lung. Thus, highly biopersistent fibers are those that are not removed from the lung as a result of dissolution. They also are not subject to breakage into shorter particles that can subsequently be removed by phagocytosis. Recent consensus panel decisions in the European Commission (EC) have standardized test protocols to determine biopersistence after exposure by inhalation and intertracheal instillation, an experimental procedure whereby the test material is washed into the lungs using a solvent such as normal saline.

METHODS OF DETERMINING BIOPERSISENCE

In the EC protocol inhalation studies, rats were to be exposed to a fiber atmosphere having defined characteristics for a period of five days. Similar requirements on instilled dose and instillation procedures are established. Biopersistence is determined by measurement of lung burden over time, using methods that determine the number of fibers and all particles present. Weighted clearance half times are determined by nonlinear regression, taking into account the observation that different classes of fibers clear with different half times. The inverse of this clearance half time is a measure of biopersistence. A unified database on fiber biopersistence (Figure 4) was prepared to define the current state of knowledge (Bernstein, 1998). Under these

circumstances, it is observed that all fibers having a weighted half time of less than ten days have no slow clearance phase.

Biopersistence can also be determined using an intraperitoneal (IP) injection protocol. This approach does not require that a respirable aerosol of fibers be created, as do the inhalation studies. However, available IP data show that biopersistence half time alone is not adequate to predict a tumorigenic response. Adequate predictive power requires inclusion of the number of injected fibers and the fiber length.

RELATIONSHIP TO HEALTH HAZARD

Analysis of available data concerning fiber properties and fiber carcinogenicity was conducted under the auspices of the EC by Bernstein *et al.* This analysis was restricted to synthetic mineral fibers ranging in solubility from ceramic fibers to slag wool. For IP injection studies, weighted biopersistence halftime, length, and number of fibers accounted for over 90% of the variation in tumor response. For chronic inhalation studies, the limited number of tumor responses required that the study be broadened to include other indicators of early lung response. Figure 5 illustrates the predicted relationship between fiber dose and tumor response for the IP data. Under these conditions, biopersistence of long fibers was seen to be an early indicator of cellular change. Figure 6 demonstrates the degree to which pulmonary fibrosis (a noncarcinogenic response) is correlated with the presence of biopersistent fibers. For the fibers examined in both inhalation and IP studies, the two measures of fiber biopersistence for long fibers were found to correlate, although IP half times were approximately twice as long as inhalation half times.

Since the inhalation studies examined included effects other than carcinogenicity, it was necessary to determine the degree of safety that using these endpoints would represent. This was done using the IP data, fiber number, fiber length, and solubility. As shown by the heavy horizontal line in Figure 4, a safety factor of 10,000 exists between a fiber that would be considered noncarcinogenic, using the EC inhalation biopersistence criteria ($WT_{1/2}$< 10 days), and a synthetic mineral fiber, which is a known animal carcinogen (micro e-glass; $WT_{1/2}$= 500

days) by inhalation. As a result of these analyses, the EC issued a directive specifying the use of these procedures in determining classification of fiber containing materials (Bjerregaard, 1997).

CHARACTERISTICS OF CHAFF FIBERS

This discussion of chaff and chaff types is not meant to be all-inclusive. The purpose here is to establish where currently used chaff fibers and those under development appear in the range of biologically important fiber properties. While a wide range of organic and inorganic materials can be considered as candidates for controlled fiber production, only metalized glass fibers will be considered. Historically, glass fibers have been widely deployed and represent the basis for current environmentally degradable chaff materials.

The fibers making up chaff are cut to specific lengths and are of specific diameters. These dimensions are dictated by their application and are closely controlled. Chaff fibers currently deployed by the Navy and Marines have diameters approximately 0.001 inch in diameter and range from 0.37-2 inch in length. The experimental environmentally degradable fibers have a diameter of approximately 1 mil (0.9 mil DVO™; 0.1 mil aluminum). Comparison of these dimensional characteristics with respirable fibers of recognized hazard indicates that the chaff fibers are extremely large in aerodynamic diameter (approximately 2500 micrometers) and thus pose no respirable hazard.

While the biopersistence of chaff fibers has not been evaluated directly, one can obtain some estimate of chaff biopersistence by analogy to other glass fibers. Chaff materials share the transverse breaking characteristic of other glass fibers, a property used in their preparation. Respirable glass fibers are of low persistence because of their propensity for transverse breakage and their consequent loss of fiber-like dimension in the lung. One may anticipate that glass based chaff fibers would exhibit the same property. The respiratory tract solubility of chaff has likewise not been determined. However, the move towards development of a degradable chaff which degrades due to atmospheric moisture will also serve to reduce the biopersistence of chaff fibers and consequently reduce their carcinogenic potential as has been demonstrated by the recent EC studies.

CONCLUSIONS

Available scientific data allow estimation of chaff inhalation toxicity. The dimensions of currently deployed chaff are extremely large compared to the deep lung deposition cut-off of five micrometers, ensuring that few, if any, chaff fibers will enter the lower respiratory tract. Because chaff dimensions are carefully controlled as part of the requirement for effectiveness, it is unreasonable to assume that anything other than the specified diameter is present in dispersed chaff.

Recent EC rulings support the observation that biopersistence is key to fiber carcinogenicity. Because the glass chaff fiber matrix is non-crystalline and chaff fibers break transversely, they should not be biopersistent. Current activities to design rapid dissolution properties into deployed chaff decrease the possibility that chaff fibers will be biopersistent. Given the low probability that chaff fibers can be inhaled into the deep lung and the case for short biopersistence half time, it can be deduced that the fibrous nature of chaff should not pose a respirable hazard.

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TABLE 1. Characteristics of some regions of the human lung

Airway	Generation	Number per Generation	Diameter (mm)	Length (mm)	Total Cross Section (cm2)	Velocity (cm/s)	Residence Time (ms)
Trachea	0	1	18	120	2.5	390	30
Main bronchus	1	2	12	48	2.3	430	11
Lobar bronchus	2	4	8.3	19	2.1	460	4.1
Segmental bronchus	4	16	4.5	13	2.5	390	3.2
Bronchi with cartilage in wall	8	260	1.9	6.4	6.9	140	4.4
Terminal bronchus	11	2 x1 0 ^{3}	1.1	3.9	20	52	7.4
Bronchioles with muscle in wall	14	16 x 10 3	0.74	2.3	69	14	16
Terminal bronchiole	16	66 x 10^{3}	0.60	1.6	180	5.4	31
Respiratory bronchiole	18	260 x 10^{3}	0.50	1.2	53	1.9	60
Alveolar duct	21	2 x 10^{6}	0.43	0.7	3.2 x 10^{3}	0.32	210
Alveolar sac	23	8 x 10^{6}	0.41	0.5	12 x 10^{3}	0.09	550

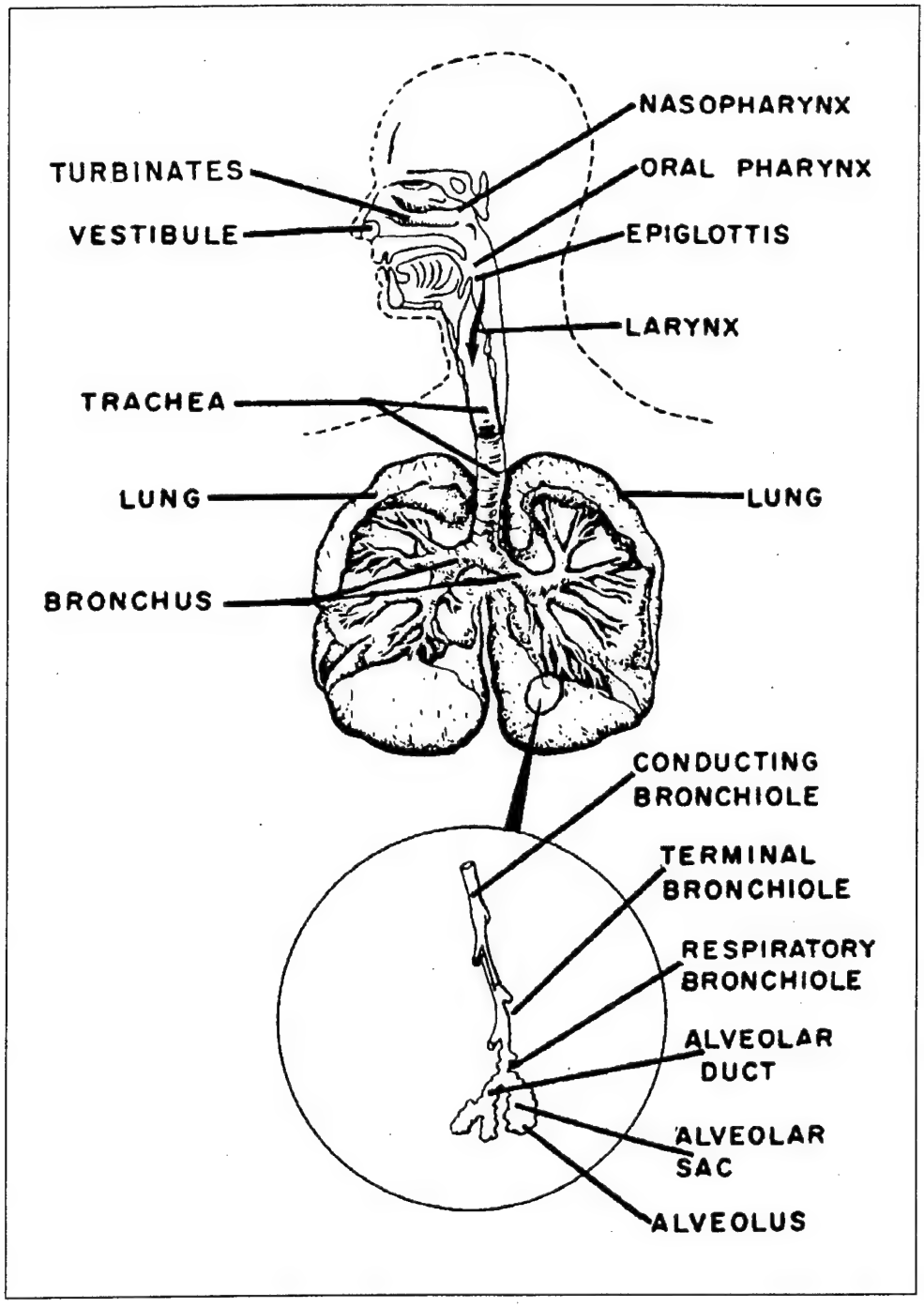

Figure 1. Key anatomical features of the human respiratory tract.

Adapted from Handbook of Air Pollution, USPHS 999-AP-44 (1968) in Hinds (1982).

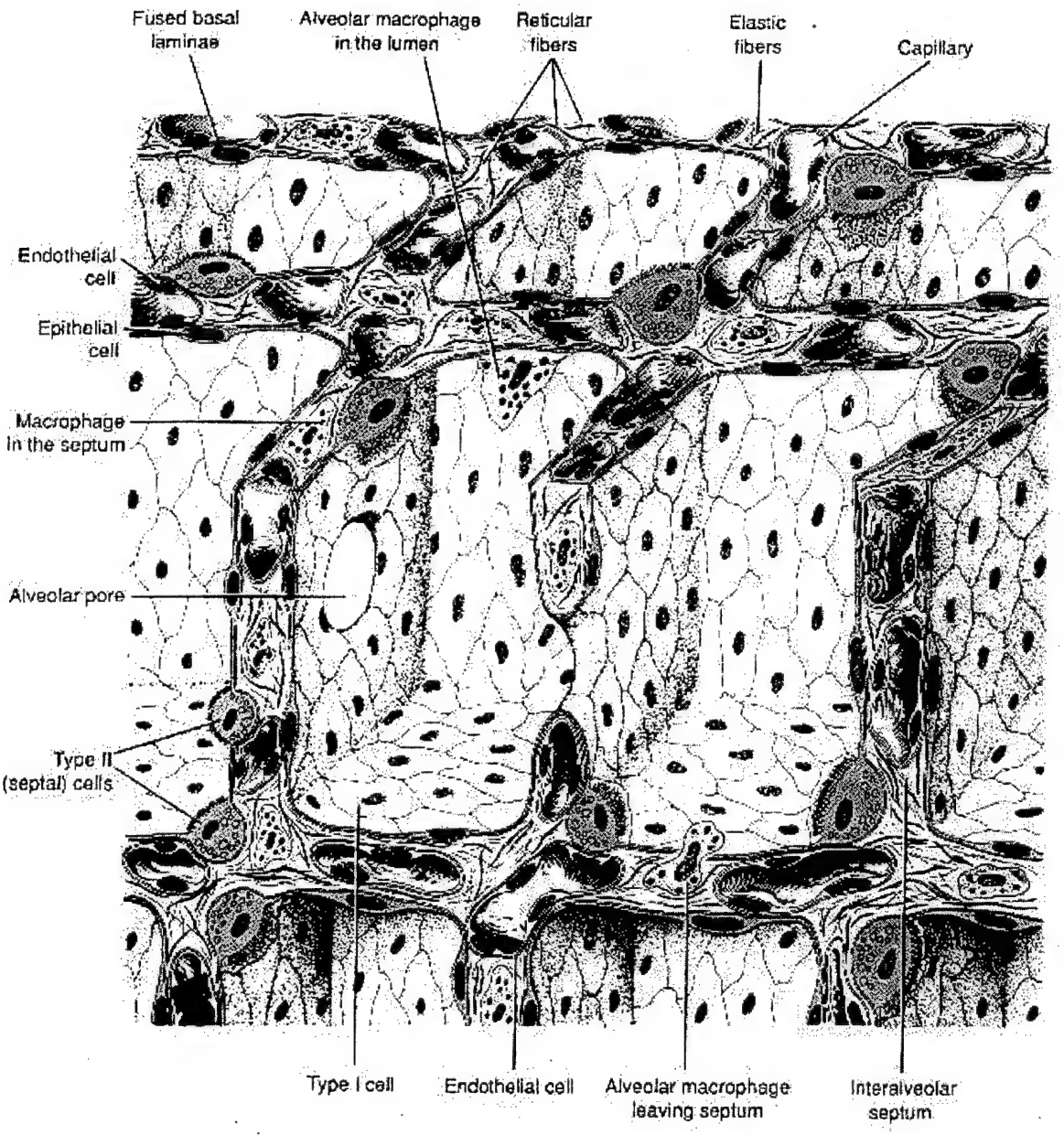

Figure 2. Relationships among air spaces, tissue spaces and blood vessels in the respiratory tissue of the lung.

Adapted from Junqueira *et al.*, 1992.

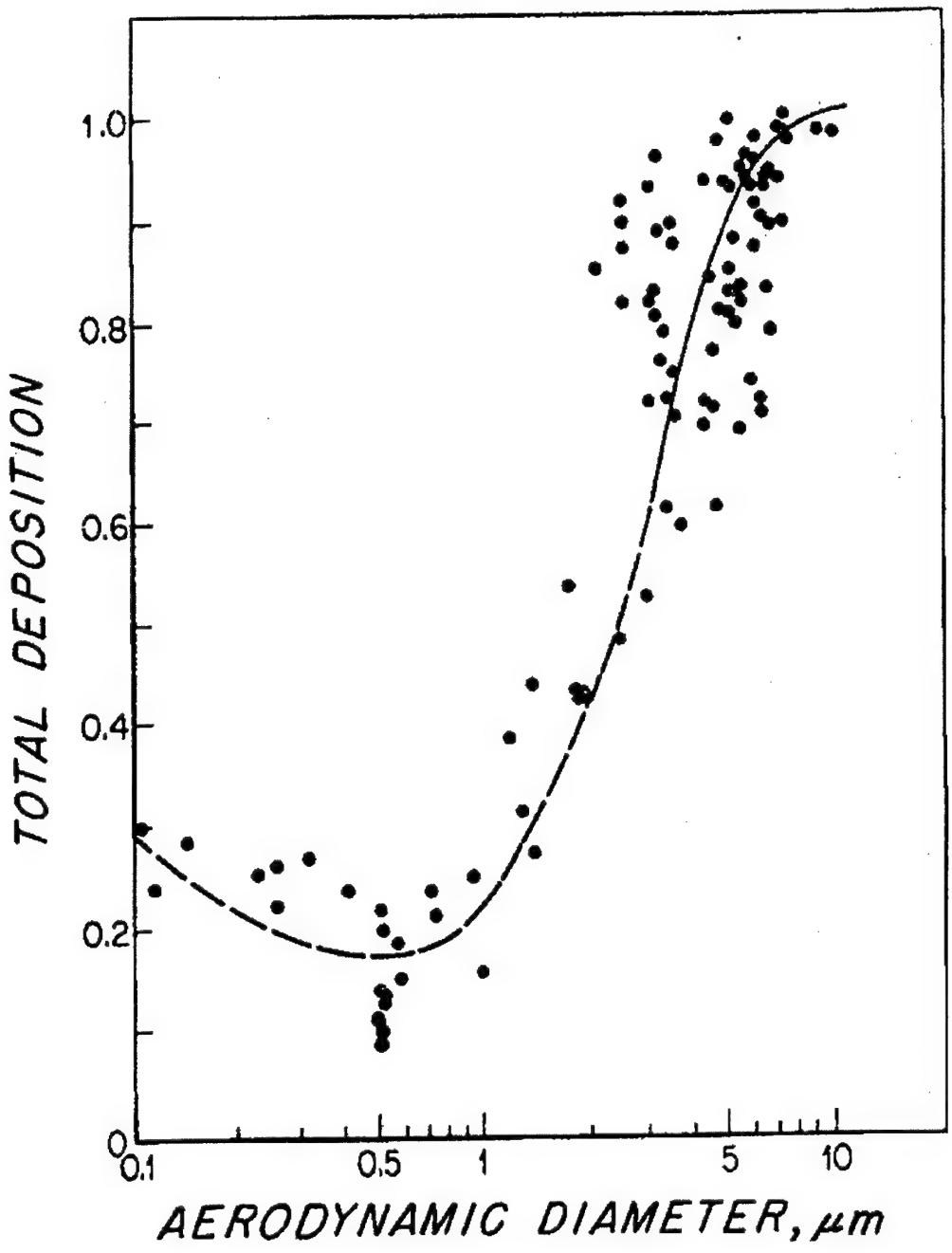

Figure 3. Respiratory tract deposition as a function of particle size.
Adapted from Hinds, 1982.

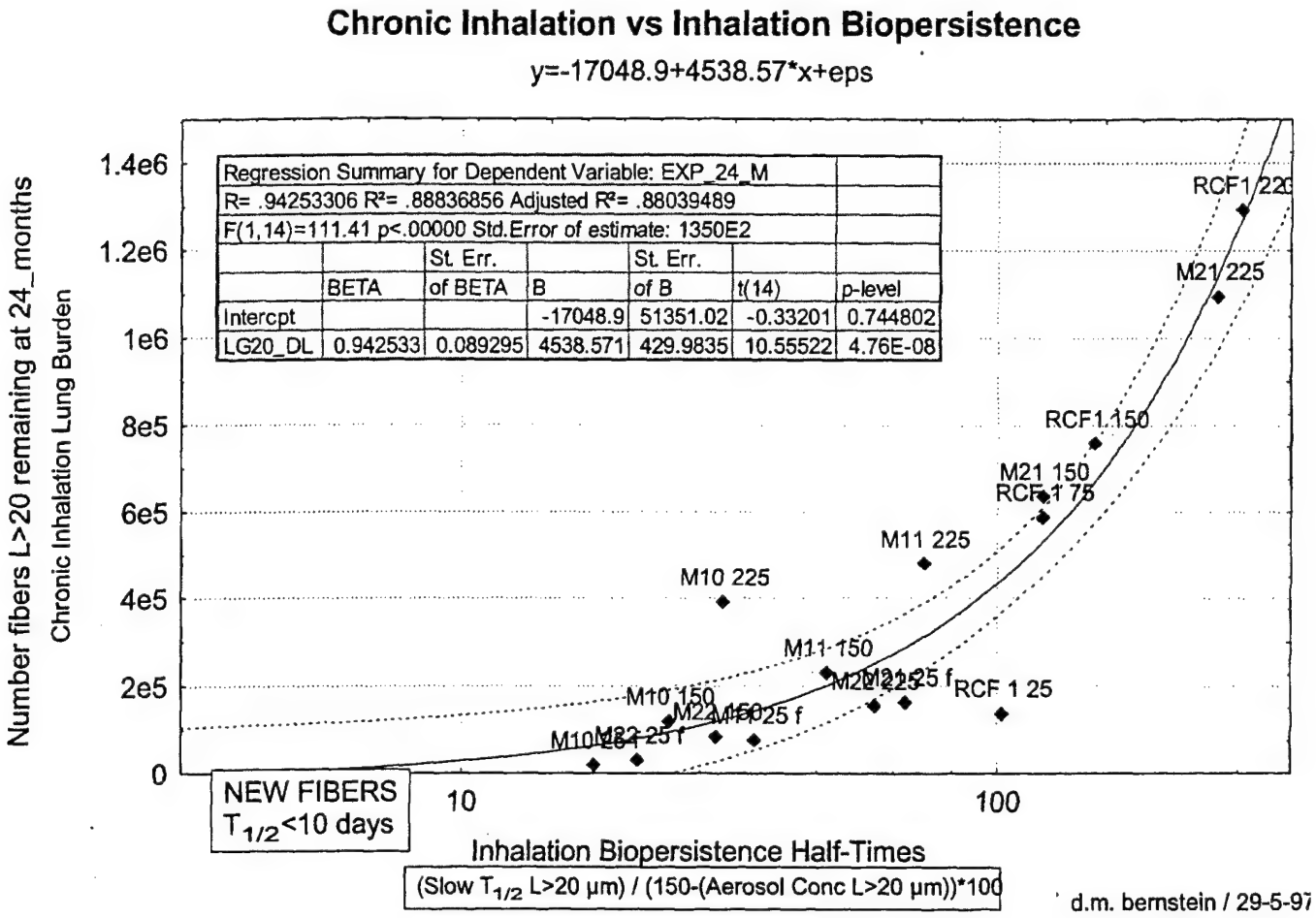

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Figure 4. Correlation of lung burden in long-term chronic inhalation studies and short-term inhalation biopersistence.

Observed Relationship between long-term inhalation lung burden and biopersistence.

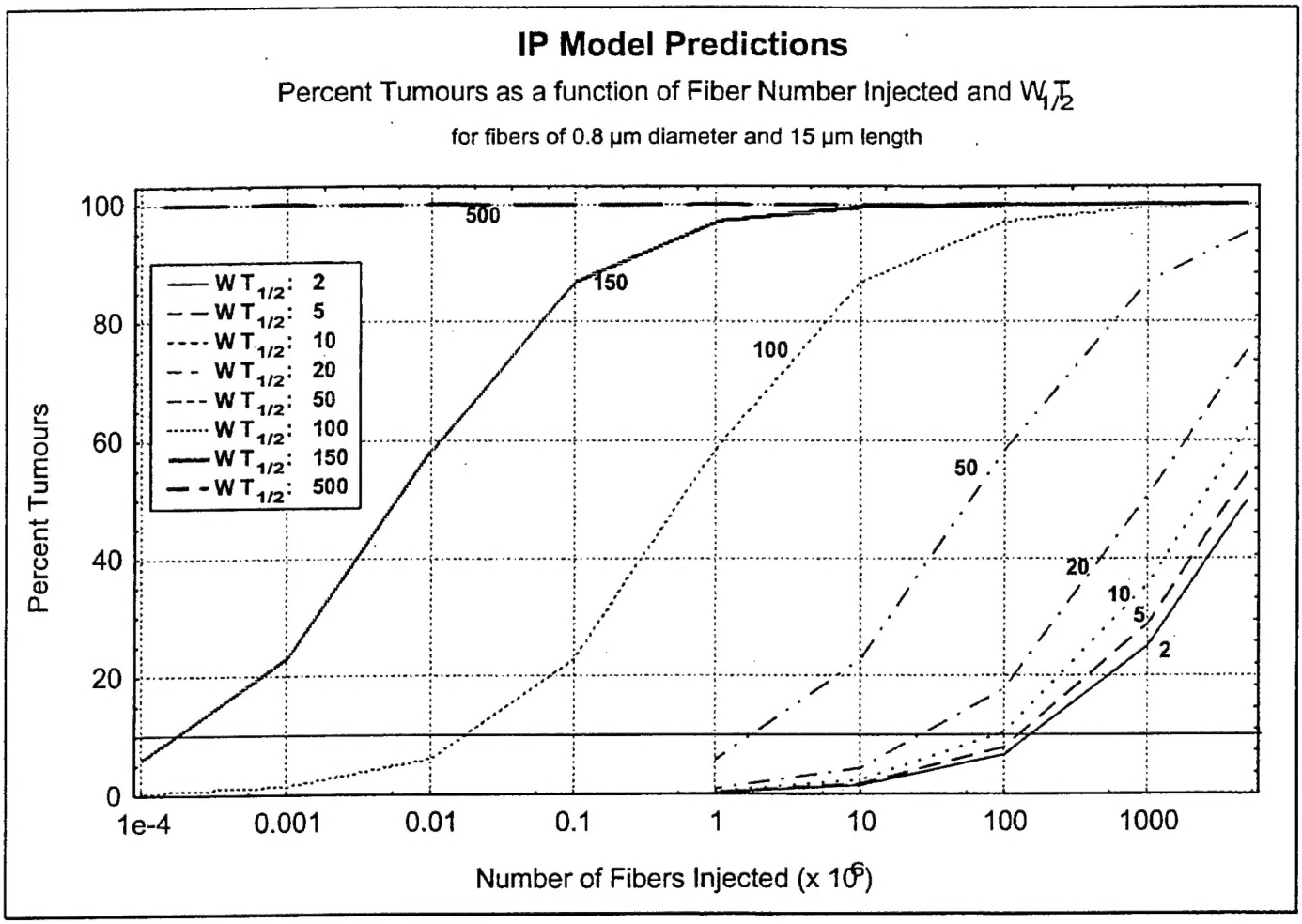

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Figure 5. Predicted relationship between IP fiber dose and tumor response.

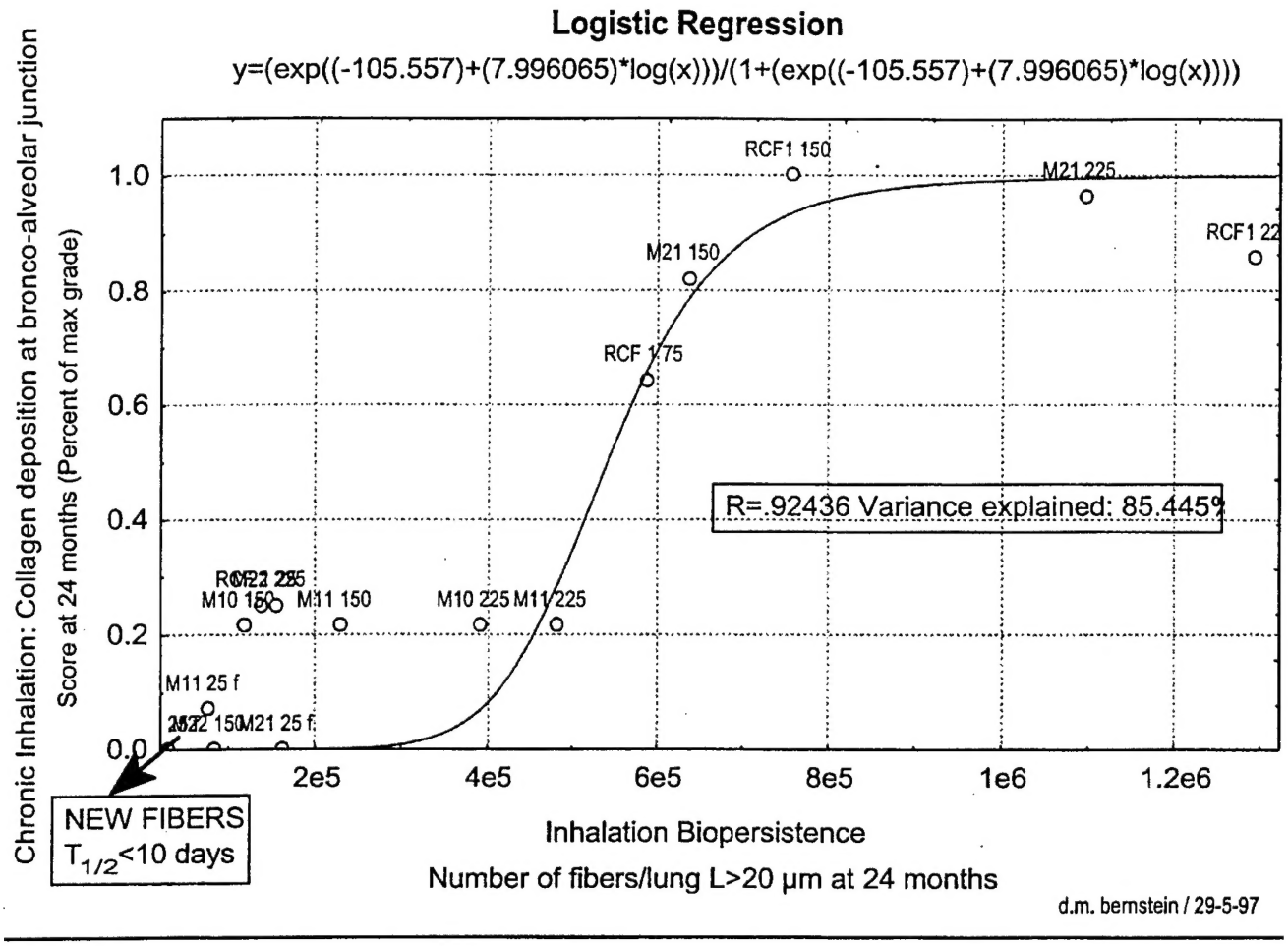

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Figure 6. Correlation of lung burden at 24 months with fibrosis at 24 months.

Long-term fiber burden (24 months after exposure is a measure of the number of biopersistent fibers.

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13. **ABSTRACT** *(Maximum 200 words)* Studies of workers occupationally exposed to asbestos revealed increasing incidence of mesothelioma, a rare form of lung cancer, whose underlying cause became clear in the 1965-1975 time frame (Selikoff *et al.*, 1972; Selikoff *et al.*, 1964; Selikoff *et al.*, 1979), creating concern as to the causes of this disease and as to the properties of asbestos leading to this disease. Asbestos exposure can cause other forms of lung disease such as fibrotic lung disease leading to severe, chronic respiratory distress. Since fibrous materials play such a key role in many facets of industrial and private life, numerous research studies of many fibers have taken place in the intervening 30 years. The purpose of this document is to provide the reader with needed background, summarize those investigations relevant to chaff health effect concerns and provide some insight as to the relevance of those concerns. Fibers differ from more spherical dust particles in their aerodynamic properties. For most dust particles, the particle's diameter and mass govern their persistence in the atmosphere. These properties also govern particle's transport properties and their ability to penetrate the respiratory system. For fibers, the fiber diameter predominately controls its aerodynamic behavior with a weak effect from fiber length. However, since the air flow through the pulmonary conducting airways is turbulent in the regions where these airways branch, fiber length plays a large role in deposition at these branch points (bifurcations). This behavior makes fiber dose to airways bifurcations particularly high. In contrast, lung deposition of spherical particles is more uniform. The research on non-asbestos insulation fibers has demonstrated that, with few exceptions, asbestos is uniquely carcinogenic. Asbestos carcinogenicity is related to the type of asbestos, with blue chrysodilite asbestos being the most toxic. Delineation of the asbestos properties leading to its unique toxicity has been the focus of much effort. Research over the past thirty years has revealed that fiber size plays a key role in fiber toxicity; fibers must be less than 0.2 micrometers in diameter and longer than 10 micrometers in length to be toxic. In part, this observation is explainable by fiber aerodynamics; fibers larger in diameter are too large to penetrate the upper respiratory tract and fibers must be long both for enhanced deposition and to foil the lung's natural defenses. The crystalline structure of fibers such as chrysodilite asbestos appears to be significant in triggering a biochemical response that leads to mesothelioma. Recent studies have provided substantial proof that fiber durability in the body is a key determinant of carcinogenicity. Fibers must persist as long particles for long times in order to reach sensitive tissues and evoke a carcinogenic response. Thus, biopersistence is key to fiber carcinogenicity. These research data allow prediction of chaff toxicity. First, chaff dimensions are carefully controlled as part of the requirement for effectiveness. The dimensions of currently deployed chaff are extremely large compared to the respirable cut-off of 0.2 micrometers, ensuring that few chaff fibers will enter the lower respiratory tract. Furthermore, the glass structure of the chaff fiber matrix is non-crystalline and should not be biopersistent. Current activities to design rapid dissolution into deployed chaff decrease the possibility that chaff fibers will be biopersistent. From these observations, it can be deduced that the fibrous nature of chaff will not pose a respirable hazard.

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